NASA-CR-203552

7N-47-CR
4&C IT
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Final Report

Report Period: 07/01/87-10/30/96

Grant NAG5-914

National Aeronautics and Space Administration
Earth Science and Applications Division
Climate Research Program

entitled

LARGE SCALE SURGFACE RADIATION BUDGET FROM SATELLITE OBSERVATIONS

Submitted by:

R. T. Pinker
Department of Meteorology
Space Sciences Building
University of Maryland
College Park, Md 20742

cc: Ms. Barbara O'Malley, Contract Administrator

Foreword

This grant was awarded in response to three separate proposals, each of approximately three years duration, with some no cost extensions. The title of the proposal that covered the first three years was:

"Mesoscale Surface Radiation Budgets from Satellite Observations: Derivation and Validation".

The title of the proposals that covered the last six years was:

"Large Scale Surface Radiation Budget from Satellite Observations".

The funding was provided under grant number NAG5-914.

The first three years could be considered as a "proof of concept" period, aimed at demonstrating that satellite based estimates of surface radiative fluxes are feasible on regional scales, both in terms of methodology, satellite data availability, and quality of inferred values. At the same time, existing methodologies have been expanded and improved, in anticipation of needs to participate in international code intercomparisons, as well as in anticipation of global data sets, that would allow to implement the methodologies on such scales, in support of climate research activities.

During the second phase of proposal duration, the feasibility to implement the model on global scale was demonstrated, model results were evaluated against ground truth, long term data sets were produced and provided to numerous users for various applications, the methodologies were evaluated in international frameworks, and the algorithms were transferred to national centers for routine processing and distribution (Version 1.1). During the last period of this grant's duration, a new version of global satellite data sets became available. In response to the upgrade of the global data sets and in response to recommendations made by the World Climate Research Program (WCRP) Working Group on Radiative Fluxes, the algorithm to derive surface shortwave fluxes was improved, and Version 2.1 was submitted to the Satellite Data Analysis Center (SDAC), NASA Langley Research Center (LaRC). This version will be run with the ISCCP D1 data.

In this final report, highlights on each activity will be presented.

TABLE OF CONTENT

1. Background - Project Objectives

The objectives of work done under this project were: to develop, validate and implement methods to derive large scale surface and top of the atmosphere shortwave radiation budgets; to use the derived fields to address issues in climate and climate change; and to develop awareness in the scientific community to the potential of this newly available information. The primary source of satellite data used for methodology development and implementation were those developed under the International Satellite Cloud Climatology Project (ISCCP) *(Schiffer and Rossow, 1985; Rossow and Schiffer, 1991)*. This effort was supported under grant NAG-5-914 from the NASA, Earth Science and Applications Division, Climate Research Program and Climate and Hydrologic Systems Branch. The above objectives were accomplished, as will be summarized in what follows.

2. Research results

2.1 Model development activity

o During the first phase of research done under this grant, a single column "proof of concept" model was expanded to work on regional scale, and was implemented with satellite data and auxiliarry input parameters that have beeen collected for this objective, as well as with the GOES ISCCP B3 data, once they became available. The derived surface shortwave fluxes have been validated against ground truth. Independent versions of the model have been developed for use with satellite observations made from additional geostationary satellite sensors (e.g., METEOSAT; GMS). This was an intermediate step, before global implementation could be considered. Model modifications were incorporated to allow participation in the Intercomparison of Radiation Codes in Climate Models (ICRCCM).

o During the second phase, the physical model to estimate surface and top of the atmosphere shortwave radiative fluxes from satellite observations was expanded for implementation on global scale. A brief description of model essentials will follow.

The methodology developed is based on the use of reflected radiation as observed by the satellite, to infer atmospheric transmittance. It requires information about the state of the atmosphere and/or the surface, to derive a relationship between transmittance and reflectance. The satellite-derived reflectance is then matched with the computed reflectance, and a transmittance is derived. The transmittance/reflectance relationship varies according to the information used about the atmosphere and the surface. The quality of the satellite observations, as well as the quality of the auxiliary input, affect the accuracy of the estimates of the surface radiation. The inference technique is based on theoretical radiative transfer schemes and is implemented spectrally. As such, it is possible to compute shortwave fluxes at spectral intervals known to be of specific significance. This is important, because current GCMs are run in a mode that seperates shortwave fluxes at 0.7 μm, to allow incorporation of newly derived satellite based surface parameters, such as the Normal Difference Vegetation Index (NDVI), and for improving parameterization of surface/atmosphere interactions. The model also allows to separate the shortwave fluxes into direct and diffuse components, which can lead to improvements of current models of radiative interaction with vegetation and oceans. Other derivable parameters are shortwave/spectral components at the top of the atmosphere, surface clear sky and all-sky albedos, and aerosol and cloud optical depths. The surface shortwave/spectral fluxes can be computed separately for clear and all-sky conditions, thus making it possible to derive information on the radiative effects of clouds, known as "cloud forcing". As yet, not all of the above capabilities of the model have been exploited , nor were there evaluated. The primary model elements have been tested in different settings. The radiative transfer component of the model was evaluated in the framework of the WCRP/ICSU sponsored evaluation of the Intercomparison of Radiative Codes in Climate Models (ICRCCM), and in the WCRP/NASA sponsored international activity on Satellite Algorithm Intercomparison *(Whitlock et al., 1990)*. The global satellite data adopted for the intercomparison activity were the ISCCP C1 data. Subsequently, this model was selected as one of two that met required accuracies on a global scale, and is now in use at the Surface Radiation Budget (SRB) Satellite Data Analysis Center (SDAC) at NASA/Langley Research Center, in support of Global Energy and Water and Water Cycle Experiment (GEWEX) activities. The global data sets are available for a period of five years during July 1983 to December 1998, and have been used by numerous scientists for evaluation, validation of large scale climate models, or for improving parameterizations of surface processes (Pinker, 1996).

o During the last part of our effort under this grant, the model was modified to allow implementation with the new version of the ISCCP C1 data, namely, the D1 data. The focus was put on preparing and testing an improved version of the Surface Radiation Budget algorithm for processing the ISCCP D1 data routinely at the SRB Satellite Data Analysis Center (SDAC) at NASA Langley Research Center. The major issues addressed were related to gap filling and to testing whether observations made from ERBE could be used to improve procedures of converting narrowband observations, as available from ISCCP, into broadband observations at the TOA. The criteria for selecting the optimal version were based on results of intercomparison of satellite inferred shortwave fluxes with ground truth. Specifically, the following was accomplished: Empirical corrections to the narrow to broadband conversions were derived by regressing TOA albedos from ERBE to those derived from the D1 data for the months for which D1 data were initially available, namely: October 1986, January 1987, June 1987, and July 1987. Separate corrections were developed for clear and cloudy skies. Empirical corrections were determined and analyzed for each contributing satellite *(GOES-6, METEOSAT-2, GMS-3, NOAA-9, NOAA-10)* separately, and all satellites combined. Corrections were also obtained and analyzed for different clear scene-types (water, vegetation, desert, snow) separately, and combined. The transformation for all satellites and surface types combined were then adopted.

In response to the recommendations of the Working Group on Radiative Fluxes of the WCRP, to evaluate the Lasis and Hansen (1974) parameterization to calculate water vapor absorption in the near infrared region of the spectrum, used in Version 1.1 of the satellite retrieval technique, the folowing was done. Three different parameterizations of water vapor absorption were tested in the GEWEX/SRB algorithm, to study the impact on the derived surface shortwave fluxes. When compared with a detailed radiative transfer model, the parameterization of Ramaswamy and Friedenreich (1992) has proved to be the most accurate. Subsequently, this latter parameterization was incorporated into the retrieval scheme. The new version of the algorithm will be provided to NASA LaRC for routine processing. An example of this product is given in Figure 1.

2.2 Scientific applications

o In a series op papers, the usefulness of surface radiation information in climate research, has been demonstarted. For example, in an early paper, "Interannual variability of solar irradiance in the Amazon Basin including the 1982/83 El Nino year *(Pinker and Laszlo,1992)*, we have studied the interannual variability of insolation over the Amazon Basin, and demonstrated, for the first time, the influence of the El Nino on the shortwave variability, and the possibility to study tropical convection. In a paper, "Shortwave cloud-radiative forcing at the top of the atmosphere, at the surface, and of the atmospheric column as determined from ISCCP-C1data" *(Laszlo and Pinker, 1992)*, the concept of cloud forcing was applied to the surface. In a companion paper *(Zhou et al., 1995)*, the changes in cloud forcing during an El Nino year are assessed. Dr. C. Rodriguez, a visiting Scientist from the University of Salamanca, Spain, under NATO sponsorship, utilized shortwave data for a period of five years over the Tropical Pacific, and detected a 30-60 day oscillation in the insolation time series over the Equatorial Pacific, associated with the propagation of convective activity *(Rodriguez et al., 1994)*.

2.3 Awareness development

o The global data of surface radiation budget parameters as produced at the WCRP/SRB Satellite Data Analysis Center (SDAC) at he NASA Langley Research Center (LaRC) *(Whitlock et al., 1995)*, have been made readily available to the scientific communirty, via the Earth Observation System Distributed Active Archive Center (DAAC) at NASA LaRc, which operates both a graphics and a character based interface to display various available options. The results can be accessed on-line as follows:

xhost+eosdis.larc.nasa.gov
telnet eosdis.larc.nasa.gov
login name: ims
password: larcims

A WCRP/SRB CD-ROM is also available as a prepackaged 46-month dataset for UNIX, Macintosh, and IBM compatible computers. Recently, a subset of this data base for a two year period 1987/88, that allows to store 3-hourly monthly means has been prepared at the University of Maryland for the Global Data Sets for Land-Atmosphere Models, ISLSCP CD-ROM, as prepared at NASA/GSFC *(Meeson et al., 1995; Sellers et al., 1995)*. The software that was developed was used to prepare the D1 version of the model for implementation at NASA LaRc, that will allow to store the 3-hourly data. The availability of these data contributed to their wide use by several scientists, for evaluation *(Rossow and Zhang, 1995; Li et al., 1995)* use in validation or parametrizations of their climate models *(Campana et al., 1994)* or for background evaluation in the context of new experiments (e. g., BOREAS) *(Moats et al., 1994).* Numerous presentations were given at scientific meetings, workshops and invited seminars, to describe various aspects of this activity to interested science groups. A summary of publications and presentations resulting from this effort is presented in the following sections.

3. Publications resulting from project

1. Pinker, R. T. and I. Laszlo, 1987. Implementation of an improved surface solar radiation model with ISCCP data. Workshop on Clouds and Climate, October 19-23, Columbia, Maryland.

2. Pinker, R. T. and I. Laszlo, 1988. Surface Radiation Budget with ISCCP Data: Towards Global implementation. XXVII COSPAR, July 18-29, 1988, Espoo, Finland.

3. Laszlo, I. and R. T. Pinker, 1989. On the optimal use of climatological information in physical models for surface solar radiation from satellites. International Radiation Symposium, Lille, France, August 18-24, 1988. Current Problems in Atmospheric Radiation. J. Lenoble and J.F. Geleyn, Editors, A. Deepak Publishing.

4. Pinker, R. T., 1989. Surface Shortwave Fluxes from Satellite Radiance Observations. COSPAR/WCRP International Workshop on Surface Radiation Budget for Climate and Global Change, Wurzburg, FRG, October 30-November 3, 1989.

5. Whitlock, C. H., Staylor, W. F., Darnell, W. L., Chou, M. D., Dedieu, G. Deschamps, P. Y., Ellis, J., Gautier, C., Frouin, R., Pinker, R. T., Laslo, I., Rossow, W. B., Tarpley, D., and LeCroy, S. R.: Intercomparison of Shortwave Satellite Algorithms With Ground Truth From the October 1986 Wisconsin FIRE/SRB Experiment. Presented at the COSPAR/WCRP International Workshop on Surface Radiation for Climate and Global Change, Wurzburg, FRG, Oct. 30-Nov. 3, 1989 ***(Invited).***

6. Rodriguez, C., I. Laszlo, and R.T. Pinker, 1990. On the variability of surface insolation in the Equatorial Pacific 7th Conference on Atmospheric Radiation, July 23-27, 1990, San Francisco, CA.

7. Laszlo, I. and R.T. Pinker, 1990. Global Aerosol Otpical depth estimated from satellites. 7th Conference on Atmospferic Radiation, July 23-27, San Francisco, CA.

8. Whitlock, C. H., Staylor, W. F., Darnell, W. L., Chou, M. D., Dedieu, G., Deschamps, P. Y., Ellis, J., Gautier, C., Frouin, R., Pinker, R. T., Laslo, I., Rossow, W. B., and Tarpley, D. 1990. Comparison of Surface Radiation Budget Satellite Algorithms for Downwelled Shortwave Irradiance with Wisconsin FIRE/SRB Surface Truth Data. Proceedings of the AMS 7th Conference on Atmospheric Radiation, San Francisco, California, July 23-27, 1990.

9. Pinker, R. T. and I. Laszlo, 1990. Improved prospects for estimating insolation for calculating regional evapotranspiration from remotely sensed data. *Agriculture and Forest Meteorology, 52, 227-251.*

10. Pinker, R.T., 1990. Satellites and our understanding of the Surface Energy Balance. *Global and Planetary Change, 82, 96-107.*

11. Laszlo, I., and R. T. Pinker, 1990. Global aerosol optical depth estimates from satellite.

Proceedings, International Geosciences and Remote Sensing Symposium, IGARSS '90, May 20-24, 1019-22.

13. Pinker, R. T., and I. laszlo, 1991. Effects of spatial sampling of satellite data on derived surface solar irradiance. *J. Atmos. Oceanic Technology, 8, 96-107.*

14. Pinker, R. T. and I. Laszlo, 1992. Modeling of surface solar irradiance for satellite applications on a global scale. *J. Appl. Meteor., 31, 194-211.*

15. Pinker, R. T. and I. Laszlo, 1992. Interannual variability of solar irradiance in the Amazon Basin including the 1982/83 El Nino year. *J. Climate, 5, 1305-13415.*

16. Laszlo, I. and R.T. Pinker, 1992. Shortwave cloud radiative forcing at the top of the atmosphere at the surface and of the atmospheric column as determined from ISCCP-C1 data. *J. Geophys. Res.,98, No. D2, 2703-2713.*

17. Pinker, R. T., W. P. Kustas, I. Laszlo, M. S. Moran, and A. R. Huete, 1993. Satellite surface radiation budgets on basin scale in semi-arid regions. *Water Resources Research, 30, 1375-1386.*

18. Whitlock, C. H., T. P. Charlock, W. F. Staylor, R. T. Pinker, I.Laszlo, R. C. DiPasquale and N. A. Ritchey, 1993. Description of WCRP Surface Radiation Budget Shortwave Data Set (Version 1.1). WMO/TD- .

19. Whitlock, C. H., T. P. Charlock, W. F. Staylor, R. T. Pinker, I. Laszlo, R. C. DiPasquale and N. A. Ritchey, 1993. Satellite estimates of solar flux input to the surface for regions in the Southern Hemisphere. 4th International Conference on Southern Hemisphere Meteorology and Oceanography, March 29-April 2, 1993, Hobart, Australia.

20. Pinker, R. T. and W. P. Kustas, 1993. Current results from satellite estimates of surface radiation for hydrological applications ***(Invited).*** AGU Spring Meeting, May 24-28, Baltimore, MD.

21. Laszlo, I. and R. T. Pinker, 1993. Global distribution of surface solar irradiance as observed from satellites. Proceedings of ISES Solar World Congress 1993, Budapest, Hungary.

22. Zhou, L., I. Laszlo, and R. T. Pinker, 1993. Shortwave radiative cloud forcing in the tropical Pacific including the 1982/83 El Nino. 8th Conference on Atmospheric Radiation, 23-28 January, Nashville, TN.

23. Laszlo, I. , and R. T. Pinker, 1993. Shortwave radiative effects of clouds as derived from ISCCP C1 data. *Adv. Space Res., 14, (1)95-(1)98.*

24. Laszlo, I. and R. T. Pinker, 1994. On the relationship between shortwave net radiative fluxes at the top of the atmosphere and at the surface. 8th Conference on Atmospheric Radiation, 23-28 January, Nashville, TN.

25. Laszlo, I., 1994. Calculation of longwave radiance at a high resolution: clear sky results. EOS/SPIE Proceedings, 2309, Passive Infrared Remote Sensing of of Clouds and the Atmosphere II, Rome, Italy, September 1994.

26. Alberta, T. T. P. Charlock, C. H. Whitlock, F. G. Rose, R. DiPasquale, R. T. Pinker, W. F. Staylor, and S. Gupta, 1994. Climate observations with GEWEX surface radiation budget projrect data, 1994. 8th Conference on Atmospheric Radiation, 74th AMS Annual Meeting, 23-28 January, Nashville, TN.

27. Kustas, W. P., R. T. Pinker, T. J. Schmugge, and K. S. Humes, 1994. Daytime net radiation estimated for a semi-arid rangeland basin with remote sensing. *Agricultural and Forest Meteorology, 11, 331-357.*

28. Campana, K. A., Y. Hou, Balasubramaniyan, R. T. Pinker, and I. Laszlo, 1994. Evaluation of NWP Model-computed shortwave radiative fluxes against satellite retrievals. 8th Conference on Atmospheric Radiation, 23-28 January, Nashville, TN.

29. Rodriguez, C., I. Laszlo,, and R. T. Pinker, 1994. Time- space variability of surface radiative fluxes over the Tropical Pacific. As above.

30. Pinker, R. T., R. Frouin and Z. Li, 1995. A Review of Satellite methods to Derive Surface Shortwave radiative Fluxes. *Remote Sensing of Environment, 51, No. 1, 108-124.*

31. Pinker, R. T., I. Laszlo, C. H. Whitlock and T. P. Charlock, 1995. Radiative Flux Opens New Window on Climate Research. *EOS, 76, No. 15, April 11.*

32 Whitlock, C. H., T. P. Charlock, W. F. Staylor, R. T. Pinker, I. Laszlo, A. Ohmura, H. Gilgen, T. Konzelman, R. C. DiPasquale, C. D. Moats, S. R. LeCroy and N. A. Ritchey, 1995. First Global WCRP Shortwave surface Radiation Budget Data Set. *Bull. Amer. Meteor. Soc. 76, No. 6, 1-18.*

33. Zhou, L., Pinker, R. T. and I. Laszlo, 1995. Shortwave Radiative Cloud Forcing in the Tropical Pacific Including the 1982/83 and 1987 El Ninos. *International Journal of Climatology, 16, 1-13.*

34. Frouin, R. and R. T. Pinker, 1995. Estimating Photosynthetically Active Radiation (PAR) of the Earth's Surface from Satellite Observations. *Remote Sensing of Environment, 51, No. 1, 98-107.*

35. Zhou, L., R. T. Pinker, and I. Laszlo, 1995. Surface albedo derived from satellite observations over China. 18th Pacific Science Congress, June 5-12, 1995, Beijing, China.

36. Laszlo, I., Pinker, R. T., Wang, Y., and Whitlock, C. H.: An Evaluation of Shortwave Surface Fluxes Derived from ISCCP Surface Properties. Presented at the Second International Scientific Conference on the Global Energy and Water Cycle. Washington, DC, June 17-21, 1996.

37. Whitlock, C. H., Cahoon, D. R., Olson, J. R., DiPasquale, R. C., Ritchey, N., Pinker, R. T., Laszlo, I., Charlock, T. P., Rose, F. G., Gupta, S. K., and Quigley, P. A.: Implementation and Products in the Version 2.0 GEWEX/SRB. Presented at the Eighth Session of the WCRP/GEWEX Radiation Panel/Working Group on Radiation Fluxes, Dublin, Ireland, July 22-26, 1996.

38. Whitlock, C. H., Cahoon, D. R., Olson, J. R., DiPasquale, R. C., Ritchey, N., Pinker, R. T., Laszlo, I., Charlock, T. P., Rose, F. G., Gupta, S. K., and Quigley, P. A.: Version 2.0 GEWEX/SRB SW and LW Algorithm Intercomparison Studies. Presented at the Fourth Session of the WCRP Radiation Projects Working Group on Data Management, Dublin, Ireland, July 29-31, 1996.

40. Laszlo, I., Pinker, R. T., and Whitlock, C. H.: Evaluation of Shortwave Radiation Fluxes Derived From the Improved Version of the ISCCP Products. International Radiation Symposium, Fairbanks, Alaska, August 19-24, 1996.

41. Pinker, R. T., 1996. Use of ISCCP data in SRB research ***(Invited).*** International Workshop on Research uses of ISCCP data sets. NASA/GISS, 15-19 April, 1996, N.Y., N.Y.

42. Pinker, R.T., 1996. Scale hopping in surface radiation budget resesearch ***(Invited).*** Workshop on scaling-up of hydrological variables using remote sensing. Institute of Hydrology, Wallingford, U. K., co-

sponsored by ISLSCP and BAHC.

43. Laszlo, I. , 1996. An overview of satellite measurement for solar radiation modeling ***(Invited).*** Satellites for Solar Energy Resource Information Workshop, April 10-11, 1996. Washington, D. C..

44. Bony, S., R. T. Pinker, and J. Schemm, 1996. Satellite assessment of re-analysis products:atmospheric hydrology and radiation. 31st COSPAR Birmingham, U.K., 15-16 July, 1996.

45. Pinker, R. T., 1996. SRB Climatology: current status and issues ***(Invited).*** IRS '96. Current problems in Atmospheric Radiation, 19-24 August, 1996, Fairbanks, Alaska.

4. Invited Seminars

1. Use of satellite observations in climate research. Department of Astronomy and Atmospheric Sciences, Yonsei University, Seoul, Korea, August 20, 1993.

2. Validating satellite inferred parameters against ground observations. Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China, August 26, 1993.

3. Review of ongoing observational activity in sub-Sahel Africa. Swiss Federal Institute of Technology, Zurich, Switzerland, September 1944.

4. Evaluation of longwave surface irradiance measurements against models, for global change applications. Swiss Federal Institute of Technology, Zurich, Switzerland, September 1994.

5. Challanges in deriving and validating fluxes of surface energy from satellites. Institute for Systems Research, University of Maryland, College Park, Md, September 30, 1994.

6. Use of surface radiation budget information in climate research. NASA/GSFC, Greenbelt, MD, October 7, 1994.

7. Overview of current capabilities to derive shortwave radiation from GOES satellites. U.S.D.A. Hydrology Laboratory, Beltsville, MD 20705, June 7, 1995.

8. Advances in Surface Radiative Flux Research: Implications for Climate Research. Institute for the Study of Planet Earth, the University of Arizona, 15 November, 1995.

9. Ongoing researcg activity on SRB. Institute for the Study of Planet Earth, the University of Arizona, 17 November, 1995.

Additional invited talks were given at numerous national and international Workshops.

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Rossow, W. B., and R. A. Schiffer, 1991. ISCCP cloud data products. *Bull. Amer. Meteor. Soc., 72, 2-20.*

Rossow, W. B,. and Y.-C. Zhang, 1995. Calculation of surface and top of the atmosphere radiative fluxes from physical quantities based on ISCCP data sets. 2. Validation and first results. *J. Geophys. Res., 97, 1167-1197.*

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Zhou, L., Pinker, R. T. and I. Laszlo, 1995. Shortwave Radiative Cloud Forcing in the Tropical Pacific Including the 1982/83 and 1987 El Ninos. *International Journal of Climatology, 16, 1-13.*

Figure 1. Monthly mean downwelling shortwave radiation (W/m**2) as derived for four months of 1986, using the ISCCP D1 version of satellite data, and Version 2.1 of the Pinker and Laszlo (1992) surface radiation budget (SRB) retrieval model.

D1 Surface Downward Flux (Wm^{-2})